TOOL-FREE CONNECTION SYSTEM FOR ROBOTIC ASSEMBLY OF LIGHTWEIGHT SHELL SYSTEMS

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Robotic assembly of shell systems requires rethinking about how shell components are connected together. This research proposes a new standardized connection system for single curvature panelised systems. A triad connection at the vertices of a hexagonally tessellated structure has three independent variables, representing the three angles of the adjacent panels. The combinations of the different variables in a single shell structure produces hundreds of solutions where each solution is an independent connection. The connection system proposed solves this problem by having three articulating connecting fingers around a central hub. This connection system relies on a parametric environment and adapts to a variety of shell geometries and curvatures. The parameters of the design dictate the joint position and only reflect on the design of the panels.

This type of standardized connection offers flexibility in the design of the structure, as well as being suitable for repurposing and use in other projects. The connections are designed for 3D printing "in-place" to reduce assembly and post-processing. The nature of this design makes it inherently easy to adjust for robotic assembly by changing the central hub features for easier manipulation by a robotic gripper. The validity of this solution is assessed in this work through tensile testing .

INTRODUCTION

Shell membrane structures are a type of architectural and engineering form characterized by their thin, curved surfaces that efficiently carry loads primarily through in-plane membrane forces (tension and compression). These structures are inspired by natural forms such as eggshells and soap bubbles, which exhibit remarkable strength and stability despite their thin profiles.

The key feature of shell structures is their ability to distribute loads across their surface, minimizing bending and maximizing structural efficiency [1]. The distribution of forces through membrane action enables shell structures to cover large spans with substantially less material use compared to other types of structures, making them an ideal choice for lightweight and sustainable designs.

Shell structures are typically constructed from materials such as reinforced concrete, steel, aluminium, or composites, the choice of material is only restricted by the desired strength, flexibility, and aesthetic considerations. However, depending on the required performance, more sustainable materials can be used such as timber [2]. The applications of shell structures are diverse and include roofs for stadiums, auditoriums, exhibition halls, and transportation terminals.

The geometry of shell structures can take various forms, either free-form or form-found shells. These geometries are designed either using principles of mathematics, physics, or computational modelling to ensure optimal performance under varying load conditions [3]. Independently of the geometry, shells can be categorized in terms of curvature into one of two categories, single curved, and double curved surfaces. The design methodology can either produce traditional vaults such as domes, and barrel vaults, or more innovative shapes such as hyperbolic paraboloids.

Regardless of geometry, shape, and curvature, shell structures share benefits in design and construction that provides freedom of design exploration and efficient loading resistance [4]:

- Material Efficiency: The curved geometry allows for a reduction in material usage without compromising structural integrity and strength.
- Aesthetic Appeal: Shell systems produce elegant forms that are visually attractive, making them a popular choice for iconic architectural projects.
- Structural Performance: They provide excellent resistance to external forces, such as wind and seismic loads.
- Adaptability: They can be adapted to various architectural and functional requirements.

Despite their advantages, designing and constructing shells requires precise engineering, advanced computational tools, and skilled labour. The analysis of these structures often involves complex calculations, considering factors such as non-linear behaviour, buckling, and long-term material performance.

Shell structures represent a perfect blend of art and engineering, combining functionality, sustainability, and beauty. Their continued evolution is driven by advancements in materials science and computational design, opening new possibilities for innovative and efficient architectural solutions. This work specifically investigates advancing their application by enabling the robotic assembly of segmented systems.

SEGMENTED SHELL STRUCTURES

Segmented shell structures are a subset of shell constructions made up of discrete elements that are joined together to form a larger structural system. Unlike monolithic shells, segmented shells are built by assembling smaller, prefabricated, or modular components, which makes them highly versatile and suitable for a wide range of architectural and engineering applications.

Segmented shells retain many advantages of traditional shell structures, such as material efficiency and aesthetics, while addressing certain challenges related to constructability, scalability, and cost. An excellent example is the livMatS Biomimetic Shell at the FIT Freiburg Centre [5] that showcases the possibility of multidisciplinary approaches to segmented shells.

Segmented shell structures offer a versatile and efficient approach to modern construction. Their modular nature, combined with advancements in materials and computational design, allows for innovative and sustainable architectural solutions. While challenges such as joint design and structural continuity persist, ongoing technological advancements continue to expand their applications and possibilities.

Lightweight shell structures are a specialised category of thin curved surfaces that derive their strength purely from their geometry. The efficient use of materials in the design of these structures produces a structurally stable structure that can withstand multiple times its own weight.

CONNECTION SYSTEMS FOR ROBOTIC ASSEMBLY

Most structures require a way to connect different elements of the design, regardless of the building method and the materials used. However, unlike traditional building methods, robotic assisted construction introduces a different challenge to the design phase of a connection system. While traditional connections like beam-column connections are designed following certain conventions, standards and experience, instead systems compatible with robotic assembly can be different. Such systems, indeed, need to follow different sets of rules, as the process of assembly has to be handled by a robotic manipulator, and the process must be solvable by the used robotic system.

PROPOSAL OF CONNECTIONS

Segmented structures typically require a larger number of connections at the joint locations determined by the design. For example, a reinforced concrete shell structure typically has connection points at the location it links to the substructure, where a segmented wooden shell structure requires connections between the elements of the superstructure as well as linkage to the substructure.

Connection systems for the substructure vary and depend mainly on the geometry of the elements and the material used. Other considerations include the self-weight of the structure, expected loading conditions, and construction method.

Considering the case in figure 1, the ECHO shell structure made of segmented 6mm thick plywood panels, individually planar and hexagonal in shape, developed and presented in Barcelona in 2019 [6]. The hexagonal shape of the panels introduces intersection vertices shared between each three adjacent panels. There are multiple ways to connect the panels while maintaining the continuity of the shell, such as edge-to-edge connections and vertex connections. Both solutions are possible and valid but have different characteristics. Edge-to-edge connections are those connecting two adjacent panels and are the most common typology used for this type of segmented structures. Although not particularly complex, edge-to-edge connections can be more difficult to implement in a system for robotic assembly (RA) . The other type is vertex connections, a less common method of connection due to the added complexity of design, however, it has its advantages when it comes to RA friendly designs.

While edge-to-edge connections join two panels on two different planes, Vertex connections join three panels on three separate planes. This added complexity can be circumvented by designing the connection in a parametric environment that, although more time consuming, it solves the problem of having to directly design many ad-hoc connections at slightly different angles for each vertex.

The shell structure shown in figure 1 was parametrically designed for manual assembly. The 144 connections join 94 panels using two-part connections attached together with a central screw and to the panels with pegs and slots (Figure 2). The 3D printed connections proved to be reliable and withstood several assembly/disassembly cycles, however, the friction fit nature of this connection makes it incompatible with any RA project.

In order to avoid the difficult task of robotic assembly of a friction fit connection, another type of connection was developed (Figure 3). A multiple part connection with moving parts that secure the panels together with a 70-degree twist of the connection shaft. This bulky solution proved to be very complex and time consuming to design, refine, and manufacture. In addition, it continued to be an ad-hoc solution, that needed to be designed for a specific set of 3 panels.

Following the previous design, an attempt to simplify the connection as much as possible while maintaining RA friendly design features resulted in a fixed connection (with no moving parts) as shown in figure 4. This attempt reduced the bulk of the connection dramatically and maintain a robotic assembly friendly design. However, even this carried over the problem of being an ad-hoc connection.

DESIGN OF A STANDARDIZED CONNECTION

Designing any type of connection requires a balance between ease of manufacturing, cost, size, strength, and standardization across the project. For example, Increasing the yielding point of the connection or one of its parts under a specific load, beyond the requirements of the project, is pointless if detrimental to other requirements. With this in mind, a new typology of connections was designed (Figure 5), focusing on standardization of the connection across the entire design.

The new connection consists of a central hub and three articulating arms. The arms rotate independently around three separate axes intersecting at a point at the centre of the hub, this point is the vertex of three adjacent panels. The 20-degree rotation of the arms, shown in figure 6, accommodates any panel angle combinations for the whole design to create a standardized design.

Each arm has a protrusion at the end, which acts as a finger, to be inserted into a slot, located at each corner of the corresponding panel. The location of the slot on the panel changes depending on the angle, however, considering the panels are already a parametrically created element of the design, the added complexity is very limited when compared to the avoided complexity of an ad-hoc connection. The shift of complexity from the design of the connection to the already parametric panels opens the possibility for further simplification of the design, with exploration in the use of different materials, and the use of advanced manufacturing processes.

MATERIALS AND MANUFACTURING

The choice of materials and manufacturing methods are interlinked, and both depend heavily on the function of the structure, expected loading scenarios, structural considerations, and sustainability. A model of a shell structure, for example, for indoors use in showrooms is not subjected to live loads, wind loads, or snow loads but need to be structurally sound. Structural stability, however, is a requirement for all projects regardless of the intended use. In the previous project, the echo shell was designed to be transportable with multiple assembly/disassembly cycles in mind, and Poplar plywood was the material of choice for its thin and lightweight properties. Based on the material choice, many manufacturing methods can be used, laser cutting was chosen, being the most accessible and fastest for that specific project. The manufacturing methods available to create the connections are much more limited, due to the small details in the connections and tight required tolerances. 3D printing, while not the fastest manufacturing method, proved to be versatile for scaled down models of any size.

Polylactic Acid or PLA was chosen for the Echo shell and continues to be used for 3D printing of connection systems due to its good mechanical properties and the ability to withstand relatively high temperatures. PLA is a biodegradable material that is most commonly used in Filament Deposit Manufacturing (FDM). PLA is typically

Figure 1: The ECHO Shell: A segmented lightweight shell structure.

Figure 2: Friction fit connection system for the ECHO shell.

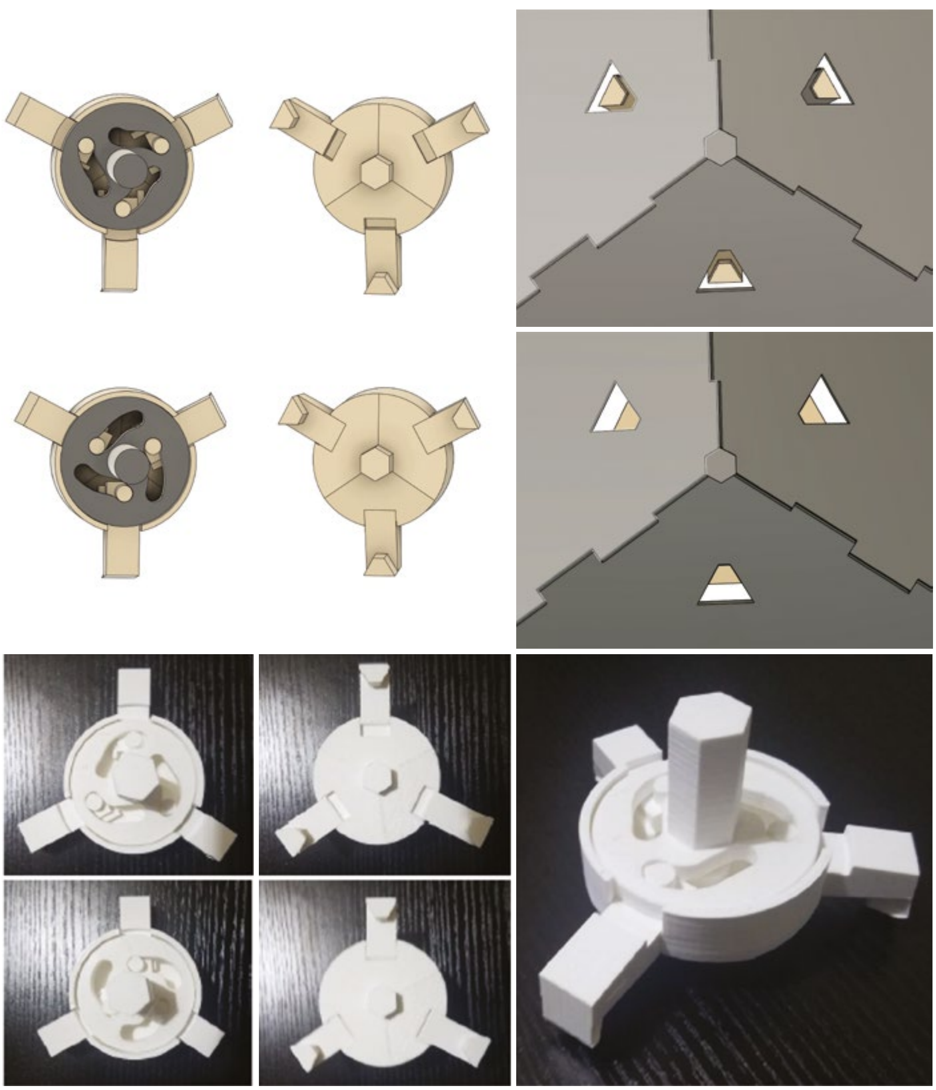

Figure 3: A non-standardized connection system for robotic assembly of shells with moving parts.

Figure 4: Ad-hoc Robotic assembly connection.

Figure 5: A standardized connection proposed for robotic assembly of shell systems.

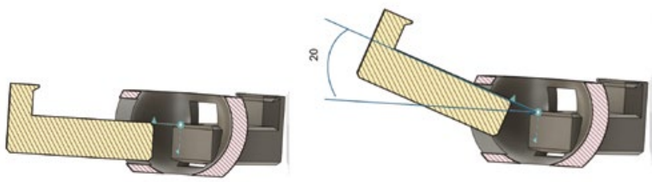

Figure 6: A cross section showing the limits of the movement of a single arm of the connection.

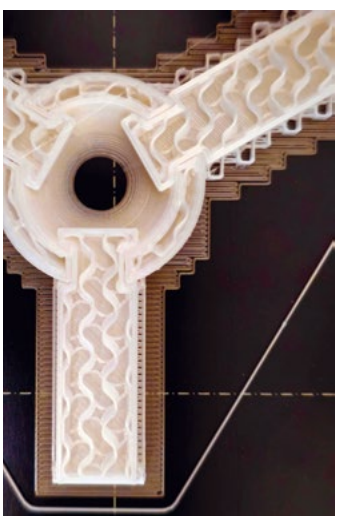

Figure 7: A top view of the connection showing the infill pattern.

Figure 8: The destructive connection testing apparatus.

manufactured using fermented plant starch, a renewable source, which makes it accessible and more sustainable than other comparable materials.

PLA is quite extensively tested for its interlayer adhesion, hardness, moisture absorption and various mechanical properties that make it ideal for fast and reliable prototyping. PLA 3D printed parts testing is also covered by multiple standards as reported in Table 1 [7].

Table 1: Material properties of the used Polylactic Acid (PLA) filament

Property	Typical Value	Method
Density [g/cm3]	1.24	ISO 1183
Moisture Absorption in 24 hours [%]	0.13	Prusa Polymers
Tensile Yield Strength for Filament [MPa]	57 ± 1	ISO 527
Hardness - Shore D	81	Prusa Polymers
Interlayer Adhesion [MPa]	17 ± 3	Prusa Polymers

The standardized connection is manufactured using an FDM 3D printer with PLA filament. A full connection is printed in "in-place" which refers to the printing of the full connection including the moving parts (arms) at the same time.

The tolerances built in the design and the accuracy of the FDM printer used makes printing in-place possible. This reduces the parts required to build the connection, and eliminates the time required for assembly. A full connection is 3D printed in one hour with minimal supports on the build plate only, which minimizes post processing to removing the supports in a few seconds.

The connection is not printed as a solid part, rather with two perimeter walls. The remaining volume of the part is occupied with an infill from the same material with a volumetric percentage of 15% and a gyroid infill pattern. The infill pattern and density remain constant for all connections tested to limit the number of variables. Although the infill pattern is shown to have an effect on the mechanical properties, this effect is more noticeable at higher infill densities [8]. Figure 7 shows the connection while being printed on the bed.

TESTING

Considering the manufacturing process and the materials used for this connection, finite element analysis should not substitute physical testing when possible. It is possible, however, in future studies to construct an FEA model that closely represents the real connection using the results of this study combined with further testing on infill patterns and percentage.

In order to better understand the failure mode and yielding stress of the panel-connection system, a testing apparatus was custom made to accommodate a connection and a freely moving section of a panel with the same coupling features found on a regular panel (Figure 8).

The apparatus is composed of two moving sections. A first section consists of a push-pull force gauge with 500N capacity, attached securely to a rigid base. The force gauge's load cell is connected to the panel with a freely rotating pin to eliminate sideway forces and reduce friction. The panel moves on a set of rails with 1-degree of freedom, in the direction of the force. The other part of the apparatus consists of a place holder for the connection that allows a pin to go through the connection's hub. The two parts mates each other using two rails that allow 1-degree of freedom in the direction of the applied force.

Each section has two points to allow the attachment of the force applying pulleys. The force applied is always a pulling force, that is applied until failure. The incremental increase of the pulling force is transferred completely through the metal parts of the apparatus and is transferred to the connection-panel coupling surfaces through the panel and the hub of the connection.

Two connections geometries for the same connection typology were tested, and the highest force registered on the force gauge was recorded. The following table summarizes the properties of Type A and Type C connections.

Table 2: The properties of the two geometries of connection tested (Type A and type C)

Connection Geometry	Arm Length (mm)	Arm Width	Arm Height	Infill (%)	No. of perim.	No. of samp.
Type A	30	12	10	15%	2	9
Type C	35	10	10	15%	2	9

Figure 9 shows the test results. The results recorded from testing for each type were averaged and the standard deviation was calculated. The samples with results higher or lower than the average by more than one standard deviation were discarded. Therefore, samples number 1 and 8 were removed for connection Type A and samples number 1 and 2 were removed for connection Type C, for being more that 1 standard deviation away from the average. The new averages were calculated based on the 7 remaining samples for each type (Figure 10).

In advance of testing, the failure points of the connection, under tension and compression, were expected to be the mating surfaces between the hub and the arm, as well as the ends of the arms that connect to the panels, as marked in red in Figure 11.

Testing has shown that the failure point (Figure 12) is consistently the fingers at the end of the arms where the loads shear the finger at a 45° angle almost in all cases of the tested connection. The failure is a combination of layer separation and cross-layer shear, which is an indication of good layer adhesion at that point.

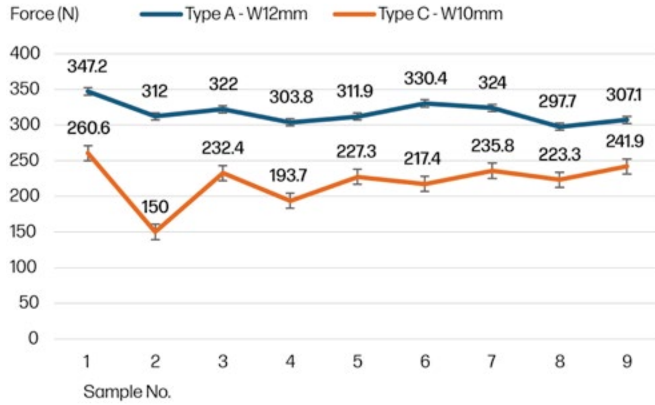

Figure 9: The results of destructive testing of the connections in Newtons.

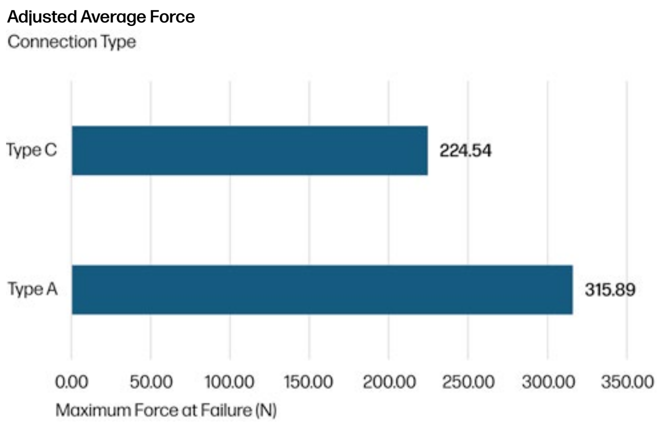

Figure 10: The adjusted average of the force required to break the two geometries of the connection tested.

Figure 11: The potential failure points of the connection.

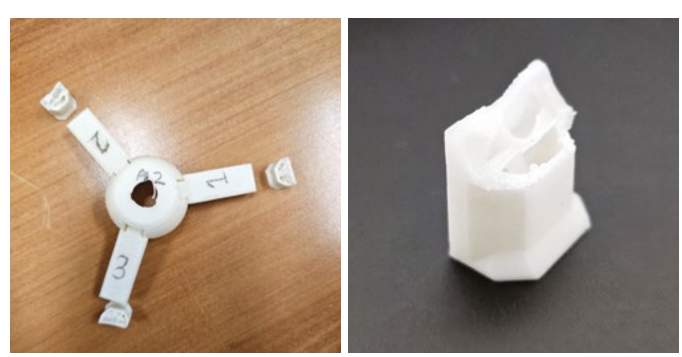

Figure 12: An image of the sample after testing showing the full connection (left) and the failure points at the fingers (right).

Based on the testing results, it was clear that Type A connections were 40% stronger than Type B connections. This is due to the increase in the width of the arm at the failure location. However, it is unclear whether the relationship between the width of the section and the strength is linear or not. Further testing with a wider range of samples is required. It is also unclear how the number of perimeters and the infill percentage affect the strength of the part in this location and whether the failure mode changes when changing these parameters.

CONCLUSION

Automating constructions is a clear trend that is starting to see initial developments, with few real applications. This study is centred on automating the assembly of discrete lightweight shell systems. The intent is twofold, developing assembly processes that can be realized with robotic manipulation and developing tools that facilitate that. Therefore, a series of connections have been proposed and prototyped with additive manufacturing. Among them, in particular, a standardized connection, to be used for connecting the vertices of segmented panels composing a single curvature surface, has proved to be easy to manufacture with very little post-processing. Mechanical testing has shown that the weakest point of the chosen type of connection was able to withstand a relatively high force. In the future, to further understand the application of AM for fast reliable prototyping, it is perceived important to investigate the effects of other variables, such as infill percentage, pattern and number of perimeter walls, on the mechanical properties of AM manufactured connections. In conclusion, this type of connection can be considered a first step towards a fully automated assembly of lightweight shells, that cuts down the time needed to assemble the structure with minimal intervention and minimal supports-structures.

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